

Analysis

Land degradation and property regimes

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Abstract

This paper addresses the relationship between property regimes and land degradation outcomes, in the context of peasant agriculture. We consider explicitly whether private property provides for superior soil resource conservation, as compared to common property and open access. To assess this we implement optimization algorithms on a supercomputer to address resource decision-making of individual households. We find that conditions exist under which private property does not lead to the best environmental outcome. Access to farming technology and off-farm employment opportunities are key factors in this result.

Keywords: Land degradation; Property regimes; Peasant agriculture; Sustainability; Household production model; Optimal control; Genetic algorithms

1. Introduction

The use and exploitation of natural resources is structured by institutions, and in particular by the institution of property. An important discussion in this regard is that concerning the link between property arrangements and prospects for long-run resource sustainability. A prevalent view on this issue is that private property possesses superior qualities to other potential property regimes, such as common property. Under private ownership, the management group is well-defined as a single agent, which can act in a unified, authoritative manner and fulfill the composition and authority axioms key to non-depleting resource exploitation (Larson and Bromley,

1990). The alleged superior performance of private property has been suggested by many authors (Demsetz, 1967; Hardin, 1968). On the other hand, opposition to this viewpoint has arisen, partly with the recognition that non-private property arrangements may fulfill the composition and authority axioms. In addition, the inferior asset problem leads to depletion of renewable assets and perhaps extinction under private property (Clark, 1973; McConnell, 1983).

Runge (1981) and Larson and Bromley (1990) have shown that arguments favoring private property confuse open access exploitation with common property usage, in which case the problems said to be associated with the commons (e.g., strict dominance of individual strategies, lack of enforcement measures) are more accurately attributed to open access (see also Ciriacy-Wantrup and Bishop, 1975). In

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fact, stable, non-degrading common property regimes have long been observed, particularly among indigenous peoples inhabiting tropical forest zones (Vayda, 1979; Hames and Vickers, 1983; Dove, 1986; Posey and Balee, 1989; Moran, 1990). The purpose of this paper is to describe and implement a methodology that can be used to assess the relative impact of various property regimes for the case of land degradation under small-scale agriculture.

The classical contrast between the relative efficiency of common property and private property relates to the existence of externalities among producers (Hardin, 1968; Runge, 1981). In the pastoral case, when technology yields separable cost functions, an individual's profit maximization occurs without reference to neighboring herd sizes, in which case individuals maintain more animals than would be the case under interdependent decision-making. If the pasture were privately owned, herd size would be less than the sum of herds under the open access.

The alleged problems associated with common property management have been widely articulated and discussed, particularly with respect to the so-called "Tragedy of the Commons," which has been extended as a general model of environmental impact and degradation (Hecht, 1985; Stonich, 1989). Actually, the tragedy of the commons is in some respects a misplaced metaphor. Excessive herd sizes and attendant environmental degradation recently observed in Africa and India (Leonard, 1985; Jodha, 1987) are well-explained by externalities arising after breakdowns in common property restrictions, in the wake of land reforms. Although land reforms have ostensibly promoted privatization, unplanned land titling and ineffective institutional controls have created situations of open access, and land degradation has occurred.

The grazing context, with its focus on externalities between like agents, is not well-suited for describing environmental impacts on tropical forests through peasant production based on shifting cultivation. The focus of this paper is on these latter agents, who are regarded as a major factor in deforestation, a land use dynamic of global impact. It is estimated that subsistence agriculture involves possibly 500 million people, with an impact on 2.4 million square kilometers. The environmental and land degradation, not to mention the deforestation which results from

induced mobility, is not necessarily the consequence of transboundary externalities between neighboring agents. Thus, the misplaced metaphor of the tragedy of the commons does not provide an adequate technical account of land degradation in this setting.

Use of fire technology and the escape of wildfire causes damage and reduced productivity over areas extending beyond the immediate boundaries of individual farmers. Peasants may compensate and intensify production in expectation of such events in a manner analogous to decision making under the open access to pastures case. The intensive use of land by small producers leading to degradation is not often explained as a response to such externalities, however, but more commonly as an endogenous response to the farming household's resource constraints and production decisions, made independently of other producers, although not of structural limitations in the social environment (e.g., Collins, 1986; Blaikie and Brookfield, 1987). Such decisions necessarily bear relation to the strength of the household's right to production outputs. These rights to appropriation, in turn, are determined by the property regime in place.

This paper presents an optimization-based, simulation methodology that can discriminate among the degradation impacts associated with three institutional regimes: namely, private property (PP), common property (CP) and the open access condition (OA). Our objectives are twofold: first, our policy objective is to show that degradation outcomes are not only associated with property regime, but also with behavioral parameters and socio-economic conditions. We show that under certain ranges of parameters and socio-economic conditions, environmental outcomes are identical, which has an implication for the land reform argument that privatization enhances environmental sustainability. Our second objective is technical. In particular, we present a new optimization method that uses recently developed, non-gradient-based search algorithms and computers clustered for parallel processing.

The paper is organized as follows. These introductory remarks are followed in Section 2 by a verbal specification of the model and by arguments allowing for model discrimination between various property regimes. Section 3 gives a technical account of the model, establishes existence and uniqueness of

solutions and presents first-order conditions for solutions. Section 4 shows model outcomes for steady states and gives methodological approaches to both infinite and finite time horizon cases. Section 5 gives results and Section 6 concludes the paper.

2. Conceptual framework

The peasant household forming the basis of the modeling effort is assumed to possess two factors of production: land and labor. The amount of land is fixed and fully utilized. The labor endowment is fixed, but hours are allocated between home labor (agricultural), wage labor and leisure. The household is taken to be an integrated unit, making unified decisions. Land productivity is variable and depends on the intensity of use; it is regarded as a renewable resource and is modeled as a logistic growth function depending on previous fertility and the amount of agricultural labor expended. Degradation is synonymous with reduced land productivity driven by intensity of use; hence, our environmental focus is on the dynamics of soil quality. The implication for deforestation is that if soil fertility is driven sufficiently low, the household must move, in the so-called model of invasive forest mobility (Myers, 1980; Walker, 1987, 1995; Walker and Smith, 1993).

Production is governed by a production function, which is taken to be Cobb-Douglas in land and labor. Off-farm labor is paid wages, and the wage rate is fixed; the household is small in relation to local markets for wage labor. Remittances and transfers are also available to the household from family members who have moved elsewhere and from government.

Household consumption consists of leisure, the agricultural product and an off-farm good. We use a specification that enables home production and off-farm goods to range from perfect substitutes (e.g., food supplements) to perfect complements (e.g., manufactured goods). The basic production/consumption configuration is taken to be identical under the three regimes (PP, CP and OA). We specify the modeling distinctions on the basis of length of planning horizon, acquisitions of human capital and agricultural productivity. PP and CP are taken to permit planning under an infinite time horizon. PP can be

passed across generations, or sold in land markets; if sold, long-run productivity is nevertheless important to the current owner since this affects price. As a rule, CP may not be sold on land markets, although it is frequently passed across generations within family units. Such transfers we take to induce planning for pensions (in kind) and familial bequests, which are consistent with infinite planning horizons.

Strictly speaking, OA requires complete absence of ownership, a situation difficult to find in the case of land resources¹. Consequently, we take the OA case to be one in which the claim to resource production is sufficiently dubious that individuals operate under a finite planning horizon. This can and does occur when land tenure is so uncertain that small producers anticipate neither the option to pass bequests nor to remain on a property beyond the foreseeable future. Such circumstances frequently arise in sites of land invasion, where poor individuals occupy unutilized land owned by wealthy individuals, by the state and even by indigenous peoples. Both the composition and authority axioms are violated in a such a situation, and in a manner consistent with the OA case, since different agents—namely a landowner and a posseiro—possess conflicting objectives with respect to the management of a particular resource. Of course, the social conflict dimension introduces costs and considerations outside the realm of production and consumption.

PP and CP are distinguished from OA by the length of planning horizon under which household agents operate. On the other hand, PP is distinguished from CP and OA by the production technology and human capital that can be brought to bear on production. With freely functioning land markets, land will be allocated to those agents with the highest level of productive capital and will thus be put to its most productive use on the basis of competition and rent maximization. Land markets are constrained in the case of CP, and may not exist, in which case land will not necessarily be allocated to those agents with the greatest capital and thus may not be put to its most productive use. In this sense, our model is a partial equilibrium one. We make no attempt to

¹ The fishery resource is closer to the OA case than any land properties.

explain the social context which limits the capital factor mobility between the various property regimes. A similar argument may hold for the OA case described. For the OA case, the technological disposition of production is ambiguous, although uncertainty in land tenure is not conducive to high capital investment to enhance levels of productivity.

3. The model

3.1. Model specification

Consider a partial equilibrium, household production model of the type described by Greenwood et al. (1993). The household's preferences are described by the utility function:

$$V = \sum_{t=0}^T \beta^t u(C_t, l_t) \quad (1)$$

where $u(\cdot) = b \ln C_t + (1-b) \ln l_t$, β is the discount rate, l_t is leisure at date t and C_t is a composite consumption good consisting of home-produced goods, C_H , and market-purchased goods, C_M , aggregated according to:

$$C_t = [\rho C_{Ht}^e + (1-\rho)C_{Mt}^e]^{1/e}, \rho \in (0, 1), e \leq 1. \quad (2)$$

The parameter e controls the household's willingness to substitute between home-produced and market-produced goods: $e = 1$ implies that these goods are perfect substitutes; $e = 0$ implies unitary elasticity of substitution between these goods (the Cobb-Douglas case); and when $e \rightarrow -\infty$ the goods are demanded in fixed proportions (the Leontief case). The parameter b in the utility function determines the agent's relative preference for consumption goods and leisure.

The household may allocate its labor to leisure time (l), producing its home good (L_H), or working outside the home in the production of market goods (L_M). Normalizing total available labor time to one gives the labor constraint:

$$1 = l_t + L_{Ht} + L_{Mt}. \quad (3)$$

Substituting Eqns. (2) and (3) into (1) yields:

$$V = \sum_{t=0}^T \beta^t u(C_{Ht}, C_{Mt}, L_{Ht}, L_{Mt}). \quad (4)$$

The household is of a primitive agrarian type with no capital storage technology. The only factor in the production process besides labor time L_H is the productivity of the soil at time t , Q_t :

$$C_{Ht} \leq c(L_{Ht}, Q_t) = AL_{Ht}^\alpha Q_t^{1-\alpha}, A > 0, \alpha \in (0, 1). \quad (5)$$

The productivity of the soil declines the more intensively the land is farmed. The land, however, has rejuvenation powers. Soil productivity is bounded below by zero, at which point it is not able to rejuvenate itself, and some upper bound \bar{Q} . A logistic equation captures the dynamics sought:

$$Q_{t+1} = q(L_{Ht}, Q_t) = Q_t + dQ_t - fQ_t^2 - gL_{Ht}. \quad (6)$$

To acquire market goods the household must sell some labor in the market at wage w_t or receive autonomous lump-sum transfer payments from outside the household, T_t . There are no financial markets (no lending or borrowing) and the household accumulates no wealth through savings. Thus, the household's budget constraint is:

$$C_{Mt} \leq w_t L_{Mt} + T_t. \quad (7)$$

The household's problem is to maximize its present discounted value of utility by allocating labor between leisure, home production and market production. Once the labor decision is made, market good consumption is determined from Eqn. (7), home good consumption is determined from Eqn. (5) and future soil productivity is determined from Eqn. (6).

More formally, the dynamic program problem faced by the household can be written as the sequence problem (SP):

$$\max_{\{Q_{t+1}\}, \{L_{Ht}\}, \{L_{Mt}\}} \sum_{t=0}^T \beta^t u(C_{Ht}, C_{Lt}, L_{Ht}, L_{Mt}) \quad (8)$$

subject to:

$$C_{Mt} \leq w_t L_{Mt} + T_t$$

$$C_{Ht} \leq c(L_{Ht}, Q_t)$$

$$Q_{t+1} = q(L_{Ht}, Q_t)$$

given $\{w_t\}$, $\{T_t\}$ and $Q_0 > 0$. The choice variables are L_{Ht} and L_{Mt} , and the state variable is Q_{t+1} .

The private property (PP) and common property (CP) problems are infinite horizon problems ($T \rightarrow \infty$), while the open access (OA) problem has a finite horizon. In addition, households under the PP model use a more productive form of home production than households under CP or OA because access to land markets increases the possibility of land being allocated to agents with higher levels of human and physical capital. The parameter A in Eqn. (5) is used to make this distinction.

The specific functions and parameters above are specified so that (1) the function c is strictly monotone increasing, twice continuously differentiable and strictly concave on some compact subset of \mathfrak{R}_+^2 , (2) q is a bounded twice continuously differentiable and strictly concave function on a compact subset of \mathfrak{R}_+^2 and (3) u is twice continuously differentiable, strictly concave and strictly increasing on \mathfrak{R}_+^4 . Since Q and L_H are bounded, C_H is bounded. Similarly, C_M is bounded since L_M is bounded, and we assume that w and T are bounded functions. Since all arguments of u are bounded, it follows that u is bounded. We assume that $0 < \beta < 1$ so that (1) is bounded. These conditions are sufficient to ensure that the solution to the sequence problem is equivalent to a similarly posed functional equation (Stokey et al., 1989), whose solution is a pair of unique differentiable singleton functions. Thus, a solution to our problem exists and is unique.

3.2. First-order conditions

At the optimum, the first two constraints of Eqn. (8) must hold with equality. Substituting these constraints into the objective function of Eqn. (8) and differentiating with respect to L_{Ht} , L_{Mt} , Q_{t+1} and λ_t (the Lagrange multiplier on the equation of motion for the state variable), yields the first-order conditions:

$$0 = u_1(t)c_1(t) + u_3(t) + \lambda_t q_1(t), \quad (9)$$

$$0 = u_2(t)w_t + u_4(t), \quad (10)$$

$$0 = \beta[u_1(t+1)c_2(t+1) + \lambda_{t+1}q_2(t+1)] - \lambda_t, \quad (11)$$

$$0 = q(t) - Q_{t+1}. \quad (12)$$

where subscripts to u indicate partial derivatives.

For finite T , Eqns. (9)–(12) hold for $t = 0, \dots, T - 1$. The first-order conditions for the terminal period are:

$$0 = u_1(T)c_1(T) + u_3(T) + \lambda_T q_1(T), \quad (13)$$

$$0 = u_2(T)w_T + u_4(T), \quad (14)$$

$$0 = q(T) - Q_{T+1}. \quad (15)$$

Along with boundary conditions on the state variable, this gives $4T + 5$ nonlinear equations in the $4T + 5$ unknowns $\{\lambda_0, \dots, \lambda_T\}$, $\{L_{H0}, \dots, L_{HT}\}$, $\{L_{M0}, \dots, L_{MT}\}$ and $\{Q_0, \dots, Q_{T+1}\}$.

For the infinite horizon case, use Eqns. (9) and (11) to eliminate λ_t so that Eqn. (9) can be rewritten as:

$$0 = u_1(t)c_1(t) + u_3(t) + \beta u_1(t+1)c_2(t+1)q_1(t) - \frac{q_2(t+1)}{q_1(t+1)}q_1(t)\beta[u_1(t+1)c_1(t+1) + u_3(t+1)]. \quad (16)$$

The solution to this dynamic Euler equation, the static Euler equation (10) and the state equation (12) are “policy” functions of the form $L_{Ht} = h(Q_t)$, $L_{Mt} = m(Q_t)$ and an equation of motion $Q_{t+1} = g(Q_t)$ which are stationary equations holding for all periods $t = 0, \dots, \infty$. The transversality conditions are satisfied since the return function is bounded and $\lim_{T \rightarrow \infty} \beta^T = 0$.

The Euler equations have a straightforward economic interpretation. The static Euler condition (10) states that the utility gained from increased market good consumption due to increased labor devoted to the market, weighted by the wage rate, must equal the utility lost due to decreased leisure time. This Euler equation is static since the decision involving market labor does not directly affect soil quality (tomorrow’s state). The first term in the dynamic Euler equation (16) represents the increased utility from an increase in the consumption of C_H due to increased labor devoted to home production. The second term represents the lost utility due to the decrease in leisure time from increased labor effort in home production. The third term represents the discounted loss in utility from decreased future consumption of C_H resulting from the reduced soil productivity due to today’s decision to farm the soil

more intensively. The final term is simply the future value of the net utility represented by the first two terms, discounted by β and scaled by $(q_2(t+1)/q_1(t+1))q_1(t) = \partial L_{H,t+1}/\partial L_H$, the effect of today's home labor choice on tomorrow's home labor choice.

4. Numerical solutions

The first-order conditions for the finite and infinite versions of this model are nonlinear difference equations which are too complex to admit closed-form solutions, and therefore require a numerical approach. In this regard, three distinct sets of numerical problems must be addressed: (1) steady-state calculations and the related comparative dynamics computations; (2) solutions of the infinite horizon problem for the policy functions and the state equation of motion; and (3) solutions to the finite horizon problem. The steady-state and infinite horizon computations are used for the PP and CP regime analyses and the finite horizon computations are used for the OA property regime analyses.

4.1. Steady-state calculations

Imposing $L_{H,t+1} = L_{Ht}$, $L_{M,t+1} = L_{Mt}$ and $Q_{t+1} = Q_t$, for all t , enables Eqns. (16), (10) and (12) to be used to compute steady-state solutions for the two choice variables, L_H and L_M , and the state variable, Q . Comparative dynamic calculations can be made by individually perturbing the parameters of the model and recomputing the steady-state values.

For base-line values of the parameters we use: $b = 0.5$, $\rho = 0.5$, $A = 1.0$, $\alpha = 0.5$, $\beta = 0.98$, $d = 1$, $f = 1$, $g = 0.5$, $w_t = 1.0$ for all t , $T_t = 0$ for all t and $e = \pm 1$. This parameterization ensures that all variables will be in the range $[0, 1]$ and that admissible steady-state values for soil quality will be in the range $[0.5, 1]$. The *scale* of home production is determined by the total factor productivity parameter A . Since Q and L_H are bounded in the interval $[0, 1]$, when $A = 1$ home production, C_H will also be bounded in this interval. The wage rate is chosen so that the returns to market labor are the same order of magnitude as the returns to home labor. In this case, with transfers fixed at zero, market consumption will

be bound in the unit interval also. With no a priori information on technology or preferences, we simply choose α , b and ρ to be one-half; the mid-point of their range. We select $\beta = 0.98$ which corresponds to a discount rate, $(1 - \beta)/\beta$, of approximately two percent per period.

In all of the steady-state calculations we perturb each parameter over its full parameter range. For instance, to compute $\partial Q/\partial \alpha$ we vary α over a grid on the unit interval. All of the partial derivatives computed turned out to be monotonic (though not necessarily linear), so in the following it is only necessary to report the sign of the partials.

When $e = 1$, C_H and C_M are perfect substitutes; rice produced at home and rice purchased at the market, for instance. As e declines, home consumption goods and market consumption goods become less substitutable. The steady-state calculations show that $\partial Q/\partial e < 0$, $\partial L_H/\partial e > 0$ and $\partial L_M/\partial e < 0$. The effects are nonlinear with most of the curvature occurring near $e = 1$. There is a qualitative difference in the behavior of the model when $e = 1$ and when $e < 1$. Subsequent calculations are made for both $e = 1$ and $e = -1$.

When $e = 1$ we find $\partial L_M/\partial b > 0$ but $\partial L_H/\partial b = 0$ and $\partial Q/\partial b = 0$. As b increases, the household prefers more consumption and less leisure. Since C_H and C_M are perfect substitutes, the household will simply choose to make a one-to-one substitution between leisure and market labor. It is not optimal to change the amount of labor devoted to home production since that involves a dynamic decision through future soil quality changes. When $e = -1$, however, C_H and C_M are no longer perfect substitutes, so the household is no longer content to devote all reduced labor time toward market consumption goods. Thus, we find $\partial L_M/\partial b > 0$ but smaller in magnitude than when $e = 1$, $\partial L_H/\partial b > 0$ and $\partial Q/\partial b < 0$. The household must sacrifice steady-state soil quality in order to produce more home goods as the demand for consumption goods is increased.

As ρ increases, the household prefers home goods more and market goods less. In other words, the slope of the indifference curve, $\partial C_H/\partial C_M$, increases. Consequently, we find $\partial L_M/\partial \rho < 0$, $\partial L_H/\partial \rho > 0$ and $\partial Q/\partial \rho < 0$. The signs of the partials are the same for all values of e , but as e becomes more negative (as C_H and C_M become less perfect substitutes) the

absolute magnitudes of the partials become smaller. When home and market goods are perfect substitutes, the household will quickly reduce labor devoted to market good production as home goods become more preferred. The household is more reluctant to reduce market labor when market goods are considered to be a distinct commodity.

The parameter α represents the elasticity of home good production with respect to home labor. As α increases, the productivity of home labor increases, so the household devotes more time to home production, $\partial L_H/\partial\alpha > 0$. However, the marginal productivity of the soil also declines ($1 - \alpha$ falls) and soil quality declines, $\partial Q/\partial\alpha < 0$. When C_H and C_M are perfect substitutes ($e = 1$), the household treats home labor and market labor symmetrically, so that $\partial L_M/\partial\alpha > 0$. When $e < 1$, the household will reduce labor devoted to market goods as home labor becomes more productive, $\partial L_M/\partial\alpha < 0$.

The parameter A represents the total factor productivity in home production. In this setting, A chosen over discrete values reflects our modeled distinction between PP and CP. When $e = 1$, we find $\partial L_H/\partial A > 0$ and $\partial Q/\partial A < 0$. Also, $\partial L_M/\partial A < 0$ since the household is perfectly willing to consume less of the market good as it becomes easier to produce the home good. When $e < 1$ the household is not so willing to give up market goods for home goods. As home goods become easier to produce, the household will spend *less* time on their production, $\partial L_H/\partial A < 0$, although the quantity of home goods produced is still increased. The slightly decreased use of home labor produces a moderate increase in the steady-state soil quality, $\partial Q/\partial A > 0$. The household also chooses to slightly increase labor devoted to market consumption, $\partial L_M/\partial A > 0$, since its overall preference for leisure is unchanged. The change in signs of these partial derivatives as e changes from one to less than one is quite an interesting result which would have been difficult to predict a priori.

Since, in this model, the wage rate, w , is equivalent to the marginal productivity of market labor, the partial derivatives of the steady-state values of L_H , L_M and Q with respect to w are qualitatively the same as those for A except opposite in sign.

As transfer payments T are increased the household will use the payments to purchase market goods

and reduce labor devoted to market production, $\partial L_M/\partial T < 0$. When C_H and C_M are perfect substitutes, the household has no incentive to change its dynamic decisions, so $\partial L_H/\partial T = 0$ and $\partial Q/\partial T = 0$. Note that as T becomes high enough, the household will devote no labor to market labor, $L_M = 0$, and simply accept the increased market goods as windfall utility, being perfectly content with its leisure decision. When $e < 1$ the household will still reduce market labor but will now increase labor devoted to home production, $\partial L_H/\partial T > 0$, in order to maintain the proper marginal relationship between home and market goods. Consequently, steady-state soil quality is slightly reduced, $\partial Q/\partial T < 0$.

The household's discount rate is computed as $(1 - \beta)/\beta$, so that large values of β reflect low discount rates and low values of β reflect high discount rates. As β increases and the discount rate declines so that the household values the future more, we find that the household is more inclined to preserve soil quality by devoting less time to home production and more time to market production, $\partial L_H/\partial\beta < 0$, $\partial Q/\partial\beta > 0$ and $\partial L_M/\partial\beta > 0$ ². The magnitudes of the effects, however, are surprisingly small. Even with extremely high discount rates, where effectively the household is making a static decision, the household is not inclined to exploit the land and then devote all its time to market production. The reason for this is that even if the household has no regard at all for the future, it is not worth the effort to drive down soil quality by over-farming since the household could do better by simply going to the market with its labor where the return on its effort is better rewarded. Much of the previous discussion and analysis in the literature has taken place in the context of models without labor markets. The explicit treatment of the labor market is an important feature which will lead our model to quite different conclusions than models where the household does not have market opportunities for its labor.

² If we allowed learning and technological change in the model, the household may be able to sustain soil quality even with increased home production. This extension, however, adds another state variable and choice variable to the model and greatly complicates the analysis.

4.2. The infinite and finite horizon cases

Under the PP and CP regimes the agents act as if they have an infinite planning horizon. The model in Section 3 is specified in such a way that the labor decisions that the agent makes given any state condition (soil quality) are stationary. In other words, for a given parameterization, whenever the agent faces a particular state, the same labor allocations will be chosen. It is this stationarity property which implies the existence of the policy functions $L_H = h(Q)$ and $L_M = m(Q)$. If we knew these policy functions, we could easily compute the agent's labor allocation decisions given any initial state.

Closed form expressions are not available for the policy functions h and m or the equation of motion for the state variable g , so these functions must be approximated numerically in order to solve the household's infinite horizon problem. One common procedure is to approximate the policy functions with Chebyshev polynomial expansions (Judd, 1992):

$$\hat{L}_i = \sum_{j=0}^n a_{ij} \psi_j \left(2 \frac{Q - Q_m}{Q_M - Q_m} - 1 \right), i = H, M \quad (17)$$

where ψ_j is the j th Chebyshev polynomial and $Q \in [Q_m, Q_M]$.

Substituting the approximate policy functions into the Euler equations (16) and (10) yields the approximate Euler residuals:

$$R_H(Q; \vec{\alpha}_H) = 0 \quad (18)$$

and

$$R_M(Q; \vec{\alpha}_M) = 0. \quad (19)$$

Since the Euler equations must hold for all possible initial values of the state, the optimization problem becomes:

$$\min_{\vec{\alpha}_H, \vec{\alpha}_M} \int_{Q_m}^{Q_M} [R_H^2(Q; \vec{\alpha}_H) + R_M^2(Q; \vec{\alpha}_M)] dQ. \quad (20)$$

We have developed a distributed parallel genetic algorithm (DPGA) to deal with complex optimization problems of this kind (Beaumont and Yuan, 1993; Beaumont and Bradshaw, 1995). In the con-

text of genetic algorithms (Holland, 1975, 1992), Eqn. (20) is the *fitness function* which we attempt to minimize with respect to the string $\{\vec{\alpha}_H, \vec{\alpha}_M\}$. Once the policy functions are found, the model may be iterated forward from any given initial condition.

The agents operating under the OA property regime act as if their planning horizon is finite. In these cases, the steady-state and infinite horizon computations are not relevant. Solving the finite horizon control problem theoretically involves solving for the $4T + 5$ unknowns using the $4T + 5$ second-order, nonlinear difference equations identified in Eqns. (9) through (15). Nevertheless, the Jacobian of this system is very poorly behaved and often goes singular during normal solution procedures. Even for a modest time horizon of ten periods, the Jacobian matrix that must be inverted is 45×45 . Our experience is that we must have very accurate starting values in order to get traditional algorithms to converge. This problem is particularly complex since there are many possible corner solutions where the household may choose to devote no labor to either market production or to home production. In addition, we have the complication of having to specify the terminal boundary condition on the state variable. In multi-state and multi-choice problems this can be nontrivial.

Fortunately, the DPGA is easily adapted to solve this problem. Substituting Eqns. (5) and (7) into the utility function so that the latter is a function of the choice variables alone and adding a "penalty" for violating the state equation (6), we write the GA fitness function as:

$$\sum_{t=0}^T \beta^t u(L_{Ht}, L_{Mt}) - (Q_{t+1} - q(L_{Ht}, Q_t))^2. \quad (21)$$

The string that the GA searches over is the vector of choice variables and the state variables, $\{L_{H0}, \dots, L_{HT}, L_{M0}, \dots, L_{MT}, Q_1, \dots, Q_{T+1}\}$. Q_0 , the initial value of the state variable, is given. No terminal conditions or complementary slackness conditions on the choice variables are required. The task is simply to choose the labor allocations to each activity, so that utility is maximized and the state equation is not violated.

Table 1
Simulation results: period 6 soil quality and period 5 labor allocations by property regime

	Wage = 1.0			Wage = 0.0		
	Q_6	L_{H5}	L_{M5}	Q_6	L_{H5}	L_{M5}
$\beta = 0.98, e = 1$						
PP	0.88	0.21	0.11	0.87	0.23	0
CP	0.95	0.10	0.34	0.86	0.24	0
OA-H	0.82	0.29	0	0.81	0.31	0
OA-L	0.86	0.11	0.37	0.73	0.44	0
$\beta = 0.98, e = -1$						
PP	0.94	0.11	0.33			
CP	0.91	0.16	0.26			
OA-H	0.93	0.13	0.33			
OA-L	0.90	0.19	0.25			
$\beta = 0, e = 1$						
PP	0.80	0.32	0	0.83	0.28	0
CP	0.95	0.10	0.35	0.83	0.28	0
OA-H	0.85	0.29	0.11	0.62	0.47	0
OA-L	0.87	0.19	0.15	0.58	0.80	0
$\beta = 0, e = -1$						
PP	0.94	0.11	0.33			
CP	0.91	0.17	0.25			
OA-H	0.66	0.31	0.30			
OA-L	0.88	0.20	0.46			

5. Simulation results

We examine the degradation impacts associated with the three property regimes by numerical simulation of the various models. The private property (PP) and common property (CP) models are infinite horizon, so we use the DPGA to solve for the policy functions under each parameterization. Then, we use those policy functions to simulate the model forward from a given initial condition. The open access (OA) model is a finite horizon model, so we use the DPGA to solve for the choice and state variables directly using the same initial condition as the PP and CP models. It is important to note that elements of our parameterization are arbitrary. We have chosen to emphasize methodological development in pursuit of hypothetical descriptions of property regime impacts. Empirical questions remain regarding appropriate parameter values, which we do not address.

The results presented in Table 1 are organized by property regime, by labor market situation, by discount rates and by the nature of the relationship between home and market goods. The results include levels of soil fertility, listed under Q_6 , the allocations of labor to on-site production L_{H5} and to market production L_{M5} . The numerical subscripts refer to observation times of model outcomes. In particular, we have arbitrarily assumed that the OA farmer plans as if he or she will abandon the land in five periods³. Thus, the soil fertility observed at the end of his or her planning period is Q_6 . We compare this to fertility under the other property regimes at the same time period. The fertility measure ranges from zero to one, with one being the maximum. We also report the percent of time that PP, CP and OA agents spend at home production labor, L_H , and market production labor, L_M , during period five. The parameterization of the equation of motion for soil quality is such that five periods is usually enough for the agent with an infinite time horizon to achieve steady-state values from any initial condition, so the PP and CP results reported in Table 1 are always very near the steady-state values.

We ran the simulations using the base-line parameters described in the steady-state computations discussion above with the following variations. The PP model uses a total factor productivity variable of $A = 1.5$ and CP uses $A = 0.5$; all other parameters in these models are the same. Since it is not clear whether the agents on the OA property would be using high or low productivity farming practices, we report results for high productivity OA, or OA-H, and low productivity OA, or OA-L. We also run the models with perfect substitution between goods, $e = 1$, and partial substitution $e = -1$. Since the discount rate is an important variable in this literature, we run the models using $\beta = 0.98$ corresponding to a discount rate of about two percent and $\beta = 0$ which

³ Observations by the second author in an area of land invasion and social conflict in the Brazilian Amazon indicated a length of land occupation of about 4 years among extremely poor settlers. Many of these individuals had probably occupied land under questionable ownership circumstances.

corresponds to an infinite discount rate. Finally, we make simulations with a market wage rate of 1.0 and with a market wage of 0 in which case there is no market opportunity to acquire goods. Simulations with both $e = -1$ and $w = 0$ are not run since it makes no sense to demand that the agent acquire market goods but provide no market return.

From the upper left portion of the Table 1 we see that, when home and market goods are perfect substitutes and when the agent has the option of selling labor in the market, the PP agent actually has a *greater* incentive to deplete soil quality than the CP agent. The reason for this is that the productivity of home production for the CP agent is sufficiently low that there is a strong incentive to spend a greater proportion of time in market good production where there is a higher rate of return on labor. As a consequence, the CP agent farms the land less intensively and depletes soil quality less. If we remove the market opportunities, the agent has no choice but to produce all goods with home production. In this case, as we can see from the upper right portion of Table 1, the CP and PP agents behave pretty much the same. The major difference is that the CP agent gets far less total consumption than the PP agent because the former is using a less productive technology.

In general, the OA agent has a greater incentive to deplete the soil than either the PP or CP agents, when the discount rates are not large (see upper two panels of Table 1). Note, however, that when home technology is not very productive, OA-L, the agent spends less time farming and more time working in the market. The high productivity agent has no incentive to go to the market since all consumption demand can be satisfied with less labor by spending all labor on the farm. When the market opportunity is removed, $w = 0$, the OA-L agent has no choice but to work the soil more intensively in order to attain the desired level of consumption, with the consequence that soil quality is driven down to the relatively low value of 0.73. Note that the CP agent, using the same technology and facing the same lack of market opportunity, chooses to deplete soil quality only to the level of 0.86. The CP agent has a greater incentive to maintain soil quality than the OA-L agent because the CP agent plans to be on the soil for a very long time whereas the OA agent knows

that after period five the land will be abandoned with no marketable salvage value.

When home and market goods are not perfect substitutes, the agent has an incentive to allocate labor to both production activities even when one activity is relatively unproductive. In this scenario we see, in the second panel of Table 1, that the PP agent now has a greater incentive to preserve the soil than the CP agent. Basically, the CP agent must work the soil a little harder using an inferior technology in order to get sufficient home goods to satisfy demands. The OA-H agent behaves about the same as the PP agent and the OA-L agent behaves about the same as the CP agent. In each case, the OA agents use the soil a bit more intensively than their PP or CP counterpart.

In the first set of simulations the agent had a very low discount rate of about two percent. Thus, the agents are quite willing to make trade-offs of today's consumption for tomorrow's consumption. In the bottom half of Table 1 we set the discount rate to infinity ($\beta = 0$), so that the agent essentially lives only for today. In the case where market opportunities exist (left side of Table 1), we see that the PP agent is affected the most when goods are perfect substitutes. In this case, the PP agent will act very much like the OA-H agent. The CP agent is not much affected by this situation since there was little incentive to exploit the soil anyway. Note that the CP agent exploits the soil to a much lesser extent than the PP agent. When market opportunities are removed (right side of Table 1), the PP and CP agents have no more incentive to exploit the soil than when the discount rate was low. Essentially, the degree to which these agents value the future is irrelevant because they have no margin over which to hedge—there is no market.

The worst scenario for soil conservation is an agent who knows that the land will be abandoned, has no regard for the future and possesses no labor market opportunities. The OA-L agent, for instance, drives soil quality down to 0.58 and spends 80 percent of the total time budget in farming. Even when the OA agent does have market opportunities but when goods are not perfect substitutes (bottom panel), if home technology is productive relative to the market (OA-H) soil quality will be driven down to the fairly low value of 0.66.

6. Implications

We can draw two main conclusions from these simulations. First, it is possible that agents may have an incentive to drive soil quality lower under a private property regime than under a common property regime. The major factor driving this result is that where a resale market exists for this land the PP agent has an incentive to use the most productive farming technology. Consequently, the land may be more intensively used and the soil quality reduced. Of course, the reduced soil quality lowers the resale value of the land, so the agent will not exploit the land below its optimal return. One implication is that private property may not be a solution to land degradation problems in land-abundant tropical frontiers. Indeed, many researchers have argued that indigenous peoples are more resource-conserving than colonists. The CP agent lacks access to this secondary land market and is thus not necessarily driven to the high productivity farming technology and so may maintain a higher soil quality than the PP agent. These results are strongly dependent on the relationship between home- and market-produced goods and the returns to market labor.

Our second conclusion is that access to a goods market outside the home is a much more important factor for soil conservation than the agent's discount rate. No matter what the discount rate, no agent will farm the soil so intensively that the return to farming becomes very low if there is a reasonably high-return market activity available. Only in the scenario where we remove market opportunities *and* put the discount rate to infinity do we observe the agent driving soil quality to very low values. This finding represents an important qualification to the inferior-asset problem identified by Clark (1973).

Our findings are highly suggestive of the independence of environmental outcomes and property regime, under certain circumstances. In this regard, we corroborate the theoretical findings of Larson and Bromley (1990). An important consideration at this point concerns the empirical setting. It is possible that the notion regarding the superior performance of private property is based on the fact that empirical conditions generally induce the alleged superior performance of private property. Simulations such as those presented in this paper, using parameter values

taken from the real world, could help shed light on this issue which is of central policy import.

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